Pressure induced softening of YB_6: pressure effect on the Ginzburg-Landau parameter $\kappa = \lambda/\xi$

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Measurements of the transition temperature T_c, the second critical filed H_{c2} and the magnetic penetration depth λ under hydrostatic pressure (up to 9.2 kbar) in the YB_6 superconductor were carried out. A pronounced and *negative* pressure effects (PE) on T_c and H_{c2} with $dT_c/dp = -0.0547(4)$ K/kbar and $\mu_0 dH_{c2}(0)/dp = -4.84(20)$ mT/kbar, and zero PE on $\lambda(0)$ were observed. The PE on the coherence length $d\xi(0)/dp = 0.28(2)$ nm/kbar was calculated from the measured pressure dependence of $H_{c2}(0)$. Together with the zero PE on the magnetic penetration depth $\lambda(0)$, our results imply that the Ginzburg-Landau parameter $\kappa(0) = \xi(0)/\lambda(0)$ depends on pressure and that pressure "softens" YB_6, e.g. moves it to the type-I direction.

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The Ginzburg-Landau parameter $\kappa = \lambda/\xi$ (λ is the magnetic penetration depth and ξ is the coherence length) is one of the fundamental parameters for superconductors. The parameter κ establishes the border between type-I ($\kappa < 1/\sqrt{2}$) and type-II ($\kappa > 1/\sqrt{2}$) superconductors by determining point where the surface energy, associated with the domain wall between the superconducting and the normal state areas, changes their sign from "plus" to "minus". Remarkably, two physical quantities entering κ (λ and ξ) depend on different properties of the superconducting material. Indeed, for BCS superconductors the zero temperature coherence length obeys the relation [1]

$$\xi(0) = \frac{\hbar\langle v_{\rm F}\rangle}{\pi\Delta(0)}. \tag{1}$$

Here, $\langle v_{\rm F}\rangle$ is the average Fermi velocity and $\Delta(0)$ is the zero temperature value of the superconducting energy gap. The zero-temperature penetration depth is given by [2, 3]

$$\frac{1}{\lambda^2(0)} = \frac{e^2}{\pi^2\hbar c^2}\oint_{S_F} ds|\mathbf{v}_F(s)|, \tag{2}$$

where the integral runs over the Fermi surface S_F. Assuming spherical Fermi surface Eq. (2) reduces to

$$\lambda^{-2}(0) \propto S_F\langle v_F\rangle. \tag{3}$$

A quick glance to Eqs. (1) and (3) reveal that $\lambda(0)$ is determined by the *normal* state properties only [S_F and $\langle v_F\rangle$] while $\xi(0)$ is determined by both – the *normal* [$\langle v_F\rangle$] and the *superconducting* [$\Delta(0)$] state properties of the material. This means that if one would be able to affect only the superconducting (normal) state properties, the Ginzburg-Landau parameter κ will change. As a consequence, superconductors can be driven to the more type-I or to the more type-II directions.

Experiments under pressure open a possibility to probe this phenomena. The reason for this can be understood by considering the simple metal superconductors, like Sn, In, Pb, Al, *etc.*, where the conduction electrons possess s, or p character. Since the s and p electrons in simple metals are nearly free, one expects approximately $v_F \propto S_F \propto V^{+2/3}$ (V is the unit cell volume). For typical values of the bulk modulus $B = 400-800$ kbar [5] it leads to $d\ln v_F/dp = d\ln S_F/dp = 2/3\cdot B^{-1}$ =0.08-0.17 %/kbar. Note that this effect is almost one order of magnitude smaller than the corresponding pressure effect on T_c: Sn ($d\ln T_c/dp = -1.30$ %/kbar), In (– 1.12 %/kbar), Pb (– 0.51 %/kbar), Al (– 2.47 %/kbar) [4]. Taking into account this and the fact that within BCS theory $\Delta(0)$ is simply proportional to T_c ($2\Delta(0)/k_BT_c = 3.52$, see e.g. [1]), Eq. (1) implies that the pressure shift of the coherence length $\xi(0)$ is almost the same as the one of T_c

$$\frac{d\ln\xi(0)}{dp} = \frac{d\ln\langle v_{\rm F}\rangle}{dp} - \frac{d\ln[\Delta(0)]}{dp} = \frac{2}{3}B^{-1} - \frac{d\ln T_c}{dp}. \tag{4}$$

From the other hand, the pressure effect on $\lambda(0)$ [see Eq. (3)] is determined by the pressure induced change of the Fermi surface and the Fermi velocity

$$\frac{d\ln\lambda(0)}{dp} = -\frac{1}{2}\frac{d\ln S_F}{dp} - \frac{1}{2}\frac{d\ln\langle v_F\rangle}{dp} = -\frac{2}{3}B^{-1}, \tag{5}$$

which appears to be an order of magnitude smaller as shown above. Thus, the much bigger pressure effect (PE) on $\xi(0)$ in comparison with the one on $\lambda(0)$ implies pressure dependence of the Ginzburg-Landau coefficient $\kappa(0)$.

Here we report studies of the effect of pressure on the Ginzburg-Landau coefficient κ in YB_6 superconductor. It was found that with increasing pressure from 0 to 9.2 kbar $\kappa(0)$ decreases by an almost 8% [from 6.17(5) to 5.70(4)], implying that pressure drives YB_6 to the *type-I* direction. The pressure effects on two quantities entering $\kappa(0)$ [$\lambda(0)$ and $\xi(0)$] were studied separately. It was

obtained that the PE on $\kappa(0)$ arises mostly from the pressure dependence of the coherence length $\xi(0)$, while no PE on the magnetic penetration depth $\lambda(0)$ (within the experimental accuracy) was observed. It was also found that in BCS superconductors for which the absolute value of the pressure shift of T_c is much bigger than $1/B$, the pressure shifts of the superconducting quantities such as T_c, $\kappa(0)$, $\xi(0)$, $H_{c2}(0)$, $dH_{c2}/dT|_{T=T_c}$ are related to each other.

Details on the sample preparation for YB_6 single crystal can be found elsewhere [6]. The hydrostatic pressure was generated in a copper–beryllium piston cylinder clamp especially designed for magnetization measurements under pressure [7]. The sample was mixed with Fluorient FC77 (pressure transmitting medium). In both below described experiments the sample-to-liquid volume ratio was of approximately 1/6.

The field–cooled (FC) and zero-field cooled (ZFC) magnetization measurements were performed with a SQUID magnetometer in fields ranging from 0.5 mT to 0.3 T and at temperatures between 1.75 K and 10 K. Two sets of magnetization under pressure experiments were performed. In the first one, small parts of the main single crystal together with the small piece of In (pressure indicator) were added to the pressure cell. In these experiments the pressure dependences of the transition temperature T_c and the upper critical field H_{c2} were studied. In the second set, the part of the single crystal was grounded in mortar and then sieved via 10 μm sieve in order to obtain small grains needed for determination of λ from magnetization measurements.

Figure 1 shows the temperature dependences of the low-field (0.5 mT FC) magnetization (a), upper critical field H_{c2} (b) and magnetic penetration depth λ (c) measured at different pressures. In the following we briefly discuss each dependence separately.

With increasing pressure magnetization curves shifts almost parallel to the lower temperatures implying the negative pressure effect on the transition temperature T_c [see Fig. 1(a)]. The corresponding pressure dependence of T_c is shown in the inset. T_c was taken from the linearly extrapolated $M(T)$ curves in the vicinity of T_c with the $M = 0$ line. The linear fit yields $dT_c/dp = -0.0547(4)$ K/kbar. Note that this value is in good agreement with $dT_c/dp \simeq -0.053(8)$ K/kbar obtained indirectly by Lortz *et al.* [6] from thermal expansion measurements.

The values of the second critical field $H_{c2}(T)$ presented in Fig. 1(b) were extracted from the FC magnetization curves $M(T,H)$ measured in constant magnetic fields ranging from 0.5 mT to 0.3 T. For each particular field H the corresponding transition temperature $T_c(H)$ was determined as described above [see Fig. 1(a)]. The value of the field H was then attributed to be the upper critical field H_{c2} at the temperature $T = T_c$. The solid lines represent fits of the WHH model [8] to the experimental data. The values of the upper critical field at $T = 0$ [$H_{c2}(0)$] obtained from the fits are plotted in the inset as the function of pressure. The linear fit yields $\mu_0 dH_{c2}/dp = -4.84(20)$ mT/kbar. The values of T_c and $H_{c2}(0)$ measured at various pressures are summarized in Table I.

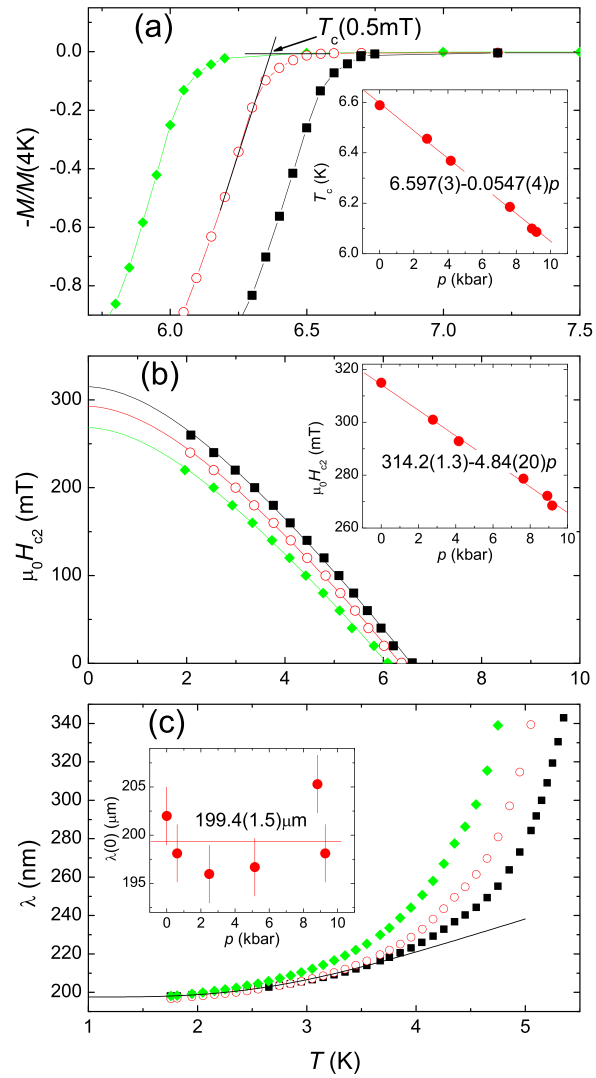

FIG. 1: (Color online) Temperature dependences of the low-field (0.5 mT FC) magnetization (a), upper critical field H_{c2} (b) and magnetic penetration depth λ measured at (from the right to the left) 0.0, 4.16 and 9.18 kbar [panels (a) and (b)] and 0.60, 5.15 and 9.15 kbar [panel (c)]. The solid lines in (b) and (c) correspond to the fit of the WHH (Ref. [8]) and the low-temperature s-wave BCS [Eq. (7)] models to the experimental data, respectively. Inserts show the corresponding pressure dependences of T_c and the zero-temperature values of $H_{c2}(0)$ and $\lambda(0)$ (see text for an explanation).

The temperature dependences of λ were calculated from the measured 0.5 mT ZFC magnetization by using the Shoenberg formula [9]:

$$\chi = -\frac{3}{2}\left(1 - \frac{3\lambda}{R}\coth\frac{R}{\lambda} + \frac{3\lambda^2}{R^2}\right), \tag{6}$$

where $\chi = M/HV$ is the volume susceptibility, V is the volume of the sample and R is the mean radius of the grains. The reducing of the grain size with pressure was taken into account in $\lambda(T)$ calculation [Eq. (6)] by using the bulk modulus value $B = 1900$ kbar [12]. Due to unknown R, the value of λ at $T = 1.7$ K and $p = 0$ was normalized to $\lambda(1.7\text{ K})$=202 nm obtained from muon-spin rotation experiments [10]. In order to obtain the zero temperature values of λ the low temperature part of the data were fitted by the standard s-wave BCS model:

$$\frac{\Delta\lambda(T)}{\lambda(0)} = \sqrt{\frac{\pi\Delta(0)}{2k_BT}}\exp\left(-\frac{\Delta(0)}{k_BT}\right). \tag{7}$$

In order to decrease the number of the fitting parameters it was assumed that $\Delta(0)$ scales with T_c as $2\Delta(0) = 4.02k_BT_c$ [11]. Note that the independence of the ratio $2\Delta(0)/k_BT_c$ of pressure was recently confirmed for $RbOs_2O_6$ [13] and ZrB_{12} [14] BCS superconductors. The resulting $\lambda(0)$ vs. p dependence is shown in the inset of the Fig. 1(c). The linear fit yields $d\lambda(0)/dp = 0.22(33)$ nm/kbar. This implies that within the accuracy of the experiment $\lambda(0)$ does not depend on pressure. The mean value of $\lambda(0)$ was found to be 199.4(1.5) nm.

Using the obtained values of $H_{c2}(0)$ (see Table I), the Ginzburg-Landau coherence length at T=0 K was calculated according to [1]:

$$\xi(0) = \sqrt{\frac{\Phi_0}{2\pi H_{c2}(0)}}, \tag{8}$$

where Φ_0 is the magnetic flux quantum. The values of $\kappa(0)$ were further calculated by using $\lambda(0) = 199.4(1.5)$ nm. It is seen (see Fig. 2) that $\kappa(0)$ decreases almost linearly from 6.17(5) at ambient pressure to 5.70(4) at $p = 9.18$ kbar. The decrease of κ thus implies that pressure "softens" the YB_6 superconductor by driving it to the type-I direction.

One should note that the observation of a zero pressure effect on $\lambda(0)$, suggests that almost the whole PE on $\kappa(0)$ in YB_6 is determined by the pressure dependence of $\xi(0)$. The PE on $\xi(0)$ is twofold. First of all, by neglecting the first term at the right hand side of Eq. (4), one can easily see that the absolute value of the PE on $\xi(0)$ is expected to be the same as the one on T_c. Second, the absolute value of $\xi(0)$ was determined from the measured $H_{c2}(0)$ by means of Eq. (8) implying, that the

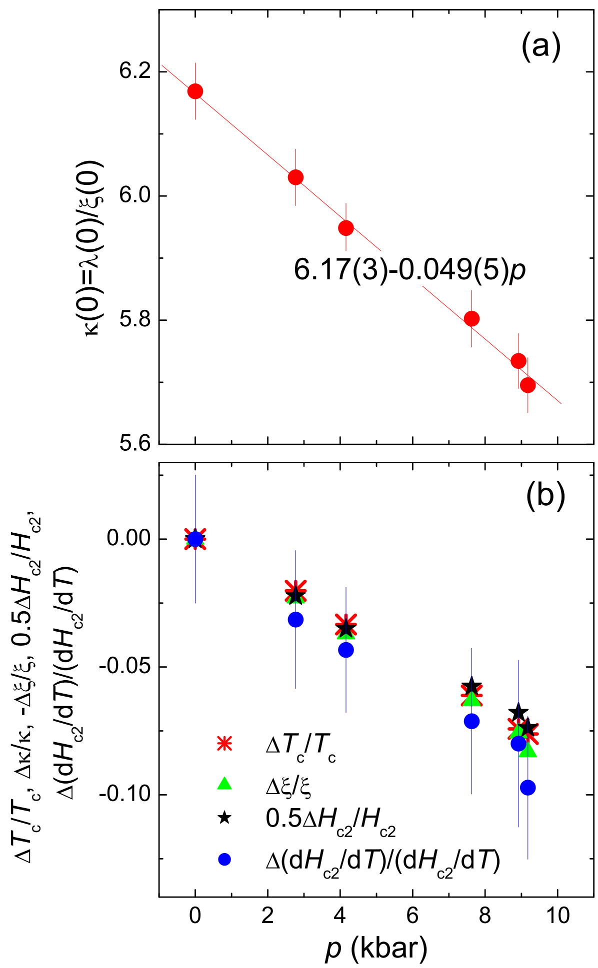

FIG. 2: (Color online) Pressure dependences of $\kappa(0)$ (a), and the relative pressure shifts $\Delta T_c/T_c$, $\Delta\kappa(0)/\kappa(0)$, $\Delta\xi(0)/\xi(0)$, $0.5\Delta H_{c2}(0)/H_{c2}(0)$ and $\Delta(dH_{c2}/dT|_{T=T_c})/(dH_{c2}/dT|_{T=T_c})$ (b). The solid line in (a) is a linear fit with the parameters shown in the Figure.

PE on $H_{c2}(0)$ is twice as big as the PE on $\xi(0)$ and, as a consequence, twice as big as the PE on T_c. The value of $H_{c2}(0)$, however, is not uniquely determined by T_c. Various superconductors, having similar T_c-s, can have the upper critical fields values that are different by a few orders of magnitude. According to the WHH theory $H_{c2}(0) \propto T_c \cdot dH_{c2}/dT|_{T=T_c}$ so that the following relation holds

$$\frac{d\ln H_{c2}(0)}{dp} = \frac{d\ln[dH_{c2}/dT|_{T=T_c}]}{dp} + \frac{d\ln T_c}{dp} = -2\frac{d\ln\xi(0)}{dp}. \tag{9}$$

This implies that in superconductors for which the absolute value of the pressure shift of T_c is much bigger than $1/B$ the pressure shifts of the superconducting quantities such as T_c, $\kappa(0)$, $\xi(0)$, $H_{c2}(0)$, $dH_{c2}/dT|_{T=T_c}$ are not in-

TABLE I: Summary of the pressure effect results (see text for details).

p (kbar)	T_{c0} (K)	$\mu_0 H_{c2}(0)$ (mT)	$\mu_0 dH_{c2}/dT$ (mT/K)	$\xi(0)$ (nm)	$\kappa(0)$
0.0	6.589(3)	315.0(1.7)	66.0(1.1)	32.32(17)	6.17(5)
2.77	6.456(3)	301.0(1.7)	63.9(1.2)	32.07(19)	6.03(5)
4.16	6.369(3)	292.9(1.3)	63.2(1.0)	33.52(15)	5.95(4)
7.63	6.186(3)	278.7(1.7)	61.3(1.3)	34.37(21)	5.80(5)
9.92	6.100(2)	272.2(1.6)	60.7(1.6)	34.77(20)	5.73(4)
9.18	6.087(3)	268.5(1.8)	59.6(1.2)	35.01(21)	5.70(4)

dependent but related to each other in accordance with:

$$\frac{d\ln T_c}{dp} \simeq \frac{d\ln\kappa(0)}{dp} \simeq -\frac{d\ln\xi(0)}{dp} \simeq 0.5\frac{d\ln H_{c2}(0)}{dp} \simeq \simeq \frac{d\ln(dH_{c2}/dT|_{T=T_c})}{dp}. \quad (10)$$

The YB_6 superconductor [$1/B$ = 1/1900kbar =0.05%/kbar [12], $d\ln T_c/dp$ =-0.83(1)%/kbar (see inset in Fig. 1(a) and Table I)] satisfy the above mentioned criteria. This implies that for YB_6 the relation (10) is expected to be correct. A quick glance at Fig. 2(b) and Table I reveals that this is exactly the case. All the quantities entering Eq. (10) are almost equal to each other within the accuracy of the experiment.

A good agreement of the experimental data with the simple above presented approach suggests that in the BCS superconductors, where condition $d\ln T_c/dp \gg 1/B$ holds, one needs to measure the pressure effect on T_c only. The pressure dependences of $H_{c2}(0)$, $dH_{c2}/dT|_{T=T_c}$, $\xi(0)$ and $\kappa(0)$ can be obtained then by using Eq. (10). In order to check the validity of Eq. (10), similar pressure experiments were performed for $RbOs_2O_6$ [10]. We have also analyzed the H_{c2} vs. p dependence for MgB_2 from Ref. [15]. In both cases a good agreement between the experimental data and Eq. (10) was observed.

To summarize, measurements of the pressure effect on the transition temperature T_c, the second critical field H_{c2} and the magnetic penetration depth λ were performed on the YB_6 superconductor. It was obtained that T_c, $H_{c2}(0)$ and the coherence length $\xi(0) \propto H_{c2}(0)^{-1/2}$ change linearly with pressure. The pressure coefficients for the superconducting transition temperature T_c, for the second critical field $H_{c2}(0)$ and for the coherence length $\xi(0)$ turned out to be $dT_c/dp = -0.0547(4)$ K/kbar, $\mu_0 dH_{c2}(0)/dp = -4.84(20)$ mT/kbar and $d\xi(0)/dp = 0.28(2)$ nm/kbar, respectively. No pressure effect on $\lambda(0) = 199.4(1.5)$ was observed within the experimental accuracy. This implies that the Ginzburg-Landau parameter $\kappa(0) = \lambda(0)/\xi(0)$ is pressure dependent, decreasing from 6.17(5) at ambient pressure to 5.70(4) at $p = 9.2$ kbar. Thus, pressure *softens* the YB_6 superconductor and drives it in the type-I direction. It was also shown that in BCS superconductors for which the absolute value of the pressure shift of T_c is much bigger than $1/B$, pressure induced shifts of the superconducting quantities such as T_c, $\kappa(0)$, $\xi(0)$, $H_{c2}(0)$, $dH_{c2}/dT|_{T=T_c}$ are related to each other.

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